Matching the Equation of State of Dense Neutron-Rich Matter Constrained by Terrestrial Experiments and Astrophysical Observations

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Naibo Zhang, TAMU-Commerce & Shandong University

EOS parameter space restricted by terrestrial experiments & theories

EOS constraints from M_{max}, R and tidal polarizability of neutron stars

Office of Science
U.S. DEPARTMENT OF ENERGY

Empirical parabolic law of the EOS of cold, neutron-rich nucleonic matter

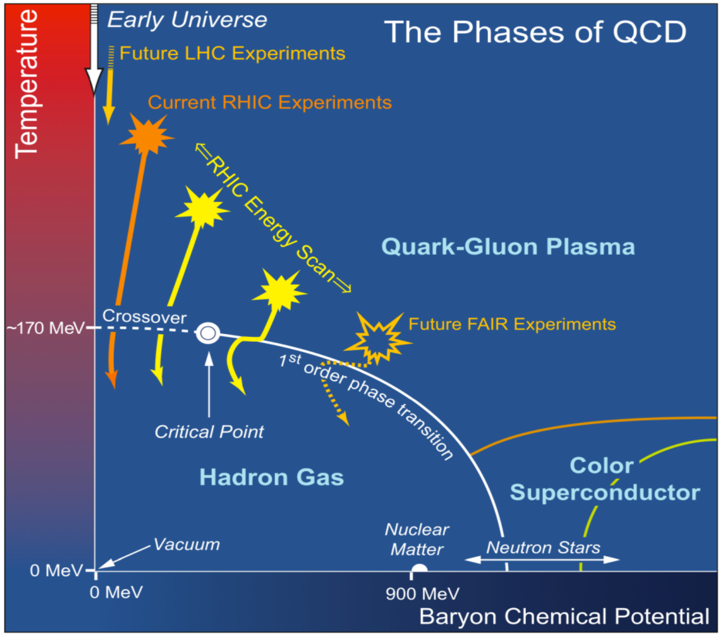
symmetry energy

Isospin asymmetry δ

$$E(\rho_n,\rho_p) = E_0(\rho_n=\rho_p) + E_{sym}(\rho)\left(\frac{\rho_n-\rho_p}{\rho}\right)^2 + o(\delta^4)$$

Energy per nucleon in symmetric matter

Energy in asymmetric nucleonic matter

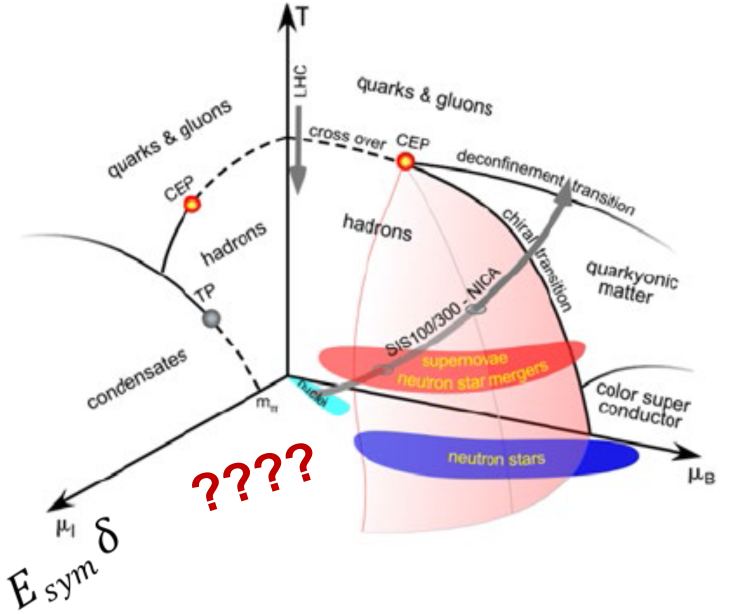


density

New opportunities

Isospin asymmetry

$\delta = (\rho_n - \rho_p)/\rho$



???

Parameterizing the EOS of symmetric matter and symmetry energy for the NS core

$$E_0(\rho) \approx E_0(\rho_0) + \frac{K_0}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{J_0}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3,$$

$$E_{\rm sym}(\rho) \approx E_{\rm sym}(\rho_0) + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{K_{\rm sym}}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{J_{\rm sym}}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3$$

Naturally approach asymptotically their Taylor expansions near the saturation density

Current status of the restricted EOS parameter space:

Low density: $K_0 = 240 \pm 20$, $E_{\rm sym}(\rho_0) = 31.7 \pm 3.2$ and $L = 58.7 \pm 28.1$ MeV

High density: $-400 \leq K_{\rm sym} \leq 100$, $-200 \leq J_{\rm sym} \leq 800$, and $-800 \leq J_0 \leq 400$ MeV

Why do not you use piecewise polytropes at high densities (HD)?

(1) The ranges of HD parameters $K_{\rm sym}$, $J_{\rm sym}$ and J_0 are so large that they cover ……….

(2) The polytropes: pressures at several fiducial densities have NO isospin dependence

(3) Need a parameterization facilitating the extraction of high density symmetry energy

The minimum model of neutron stars: The pressure in the npeμ matter:

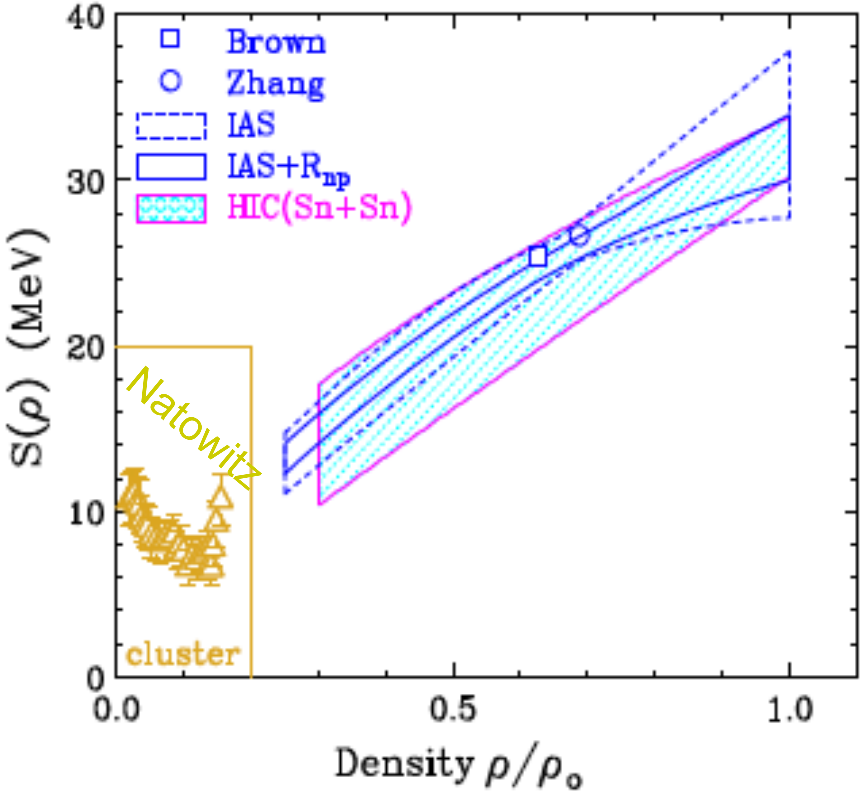
$$P(\rho,\delta) = P_0(\rho) + P_{\rm asy}(\rho,\delta) = \rho^2\left(\frac{\partial E}{\partial \rho}\right)_\delta + \frac{1}{4}\rho_e\mu_e$$

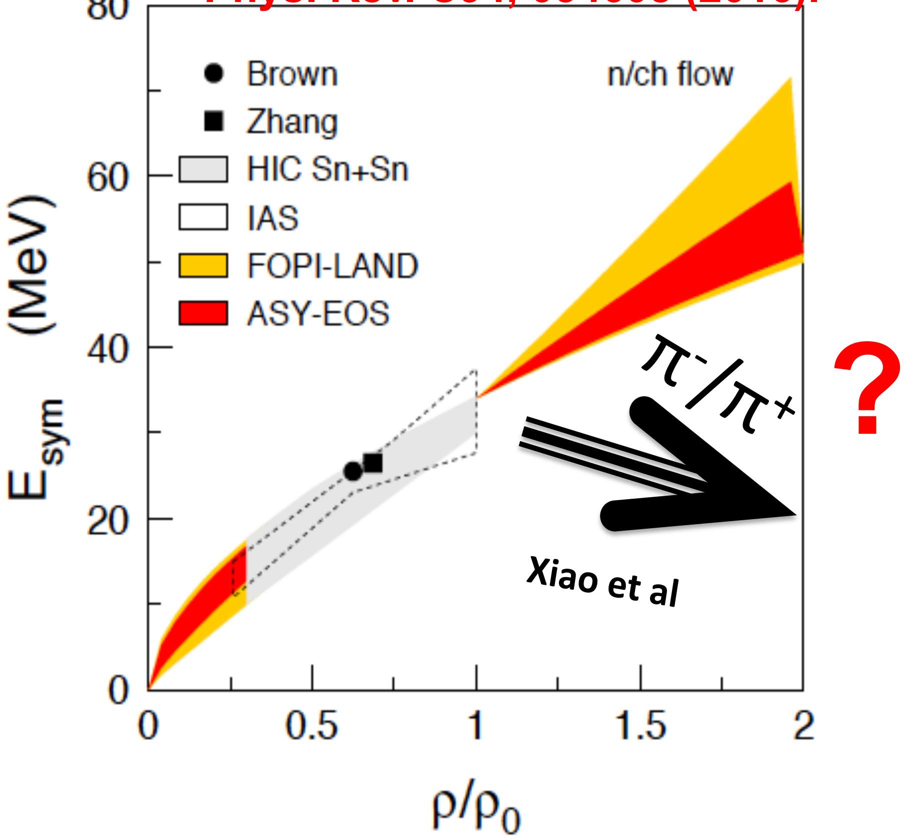
$$= \rho^2\left[E'(\rho,\delta=0) + E'_{\rm sym}(\rho)\delta^2\right] + \frac{1}{2}\delta(1-\delta)\rho E_{\rm sym}(\rho),$$

What is the density dependence of symmetry energy?

Indications of experiments (model dependent)

P. Russotto et al. (ASY-EOS Coll), Phys. Rev. C94, 034608 (2016).





Betty Tsang et al., PRC 86, 105803 (2012).

Chuck Horowitz et al., JPG: 41 (2014) 093001

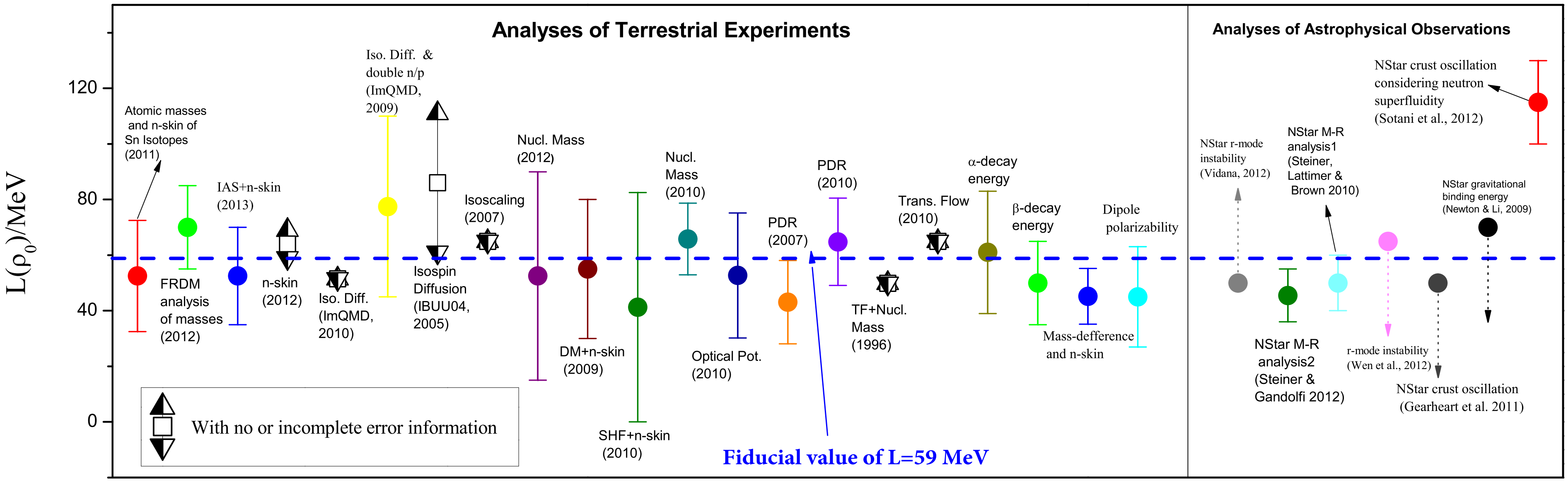
Z.G. Xiao et al, based on GSI/FOPI data Phys. Rev. Lett. 102, 062502 (2009).

Constraints on $E_{sym}(\rho_0)$ and L based on 29 analyses of data

Fiducial values as of Aug. 2013

$$E_{sym}(\rho_0) \approx 31.6 \pm 2.66 \text{ MeV}$$

$$L \approx 2\, E_{sym}(\rho_0) = 59 \pm 16 \text{ MeV}$$



Bao-An Li and Xiao Han, **Phys. Lett. B727 (2013) 276-281**

$$E_{\rm sym}(\rho) = E_{\rm sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho}{\rho_0} - 1\right) + \frac{K_{\rm sym}}{18}\left(\frac{\rho}{\rho_0} - 1\right)^2 + \frac{J_{\rm sym}}{162}\left(\frac{\rho}{\rho_0} - 1\right)^3$$

Constraints on $E_{sym}(\rho_0)$ and L based on 53 analyses of data

Fiducial values as of Oct. 12, 2016

$E_{sym}(\rho_0) \approx 31.7 \pm 3.2$ MeV

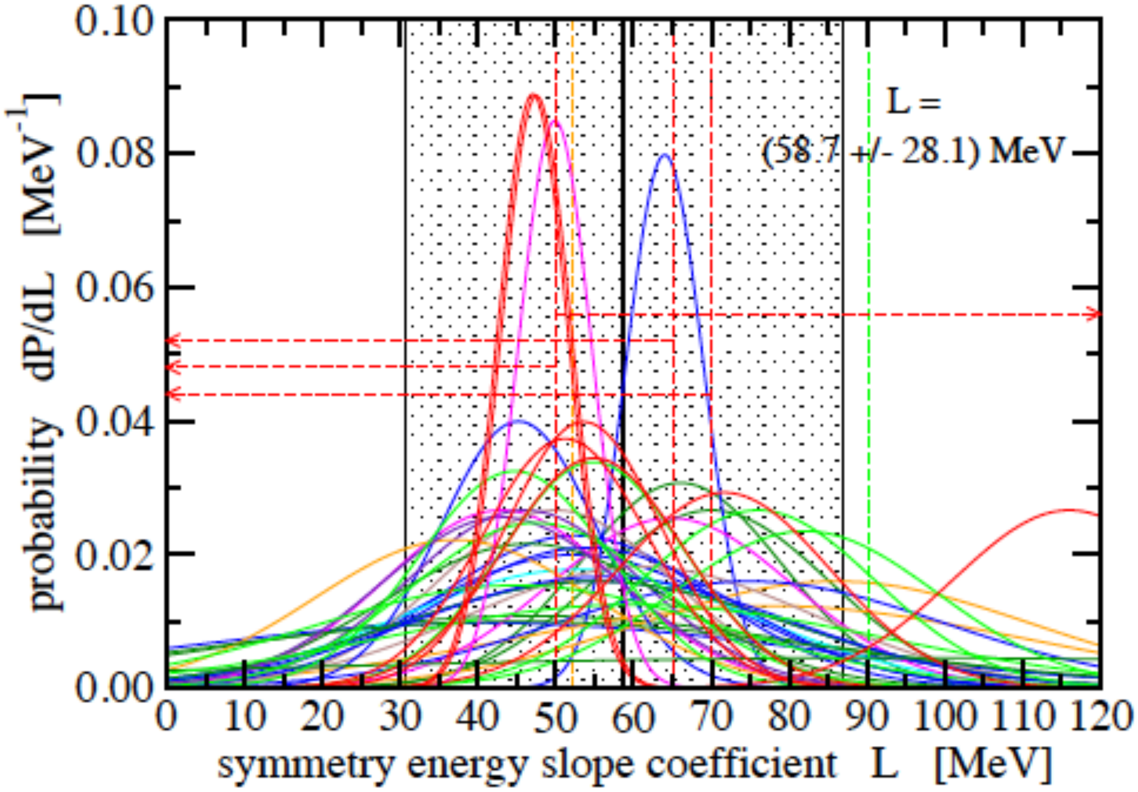
$L = 58.7 \pm 28.1$ MeV

Assuming:

(1) Gaussian distribution of L

(2) Democratic principle

(treat & trust everyone/publication equally)



M. Oertel, M. Hempel, T. Klähn, S. Typel

Review of Modern Physics 89 (2017) 015007

Isoscalar Excitation Modes of Nuclear Resonance

$K_0 = 240 \pm 20$ MeV

$$E_{ISGMR} \approx \sqrt{\frac{K_A}{m < r^2 >}}$$

$$E_{ISGDR} \approx \sqrt{\frac{3}{7}\frac{K_A + (27/25)\varepsilon_F}{m < r^2 >}}$$

$$K_A = K_{vol} + K_{surf} A^{-1/3} + K_\tau \delta^2 + K_{Coul} \frac{Z^2}{A^{4/3}}$$

Isospin dependence of incompressibility

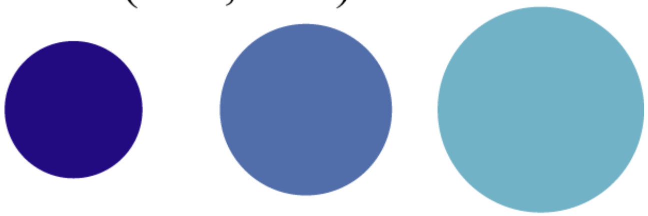
$$K_\tau = K_{\rm sym} - 6L(\rho_0) - \frac{J_0 L(\rho_0)}{K_0}$$

$$K_\tau = -550 \pm 100 \text{ MeV}$$

Nothing conclusive about K_{sym}

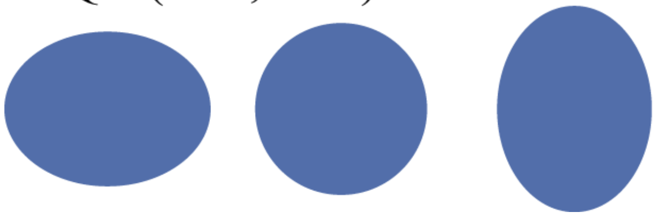
Isoscalar Giant Resonances:

ISGMR (T=0, L=0)



ISGDR (T=0, L=1)

ISGQR (T=0, L=2)

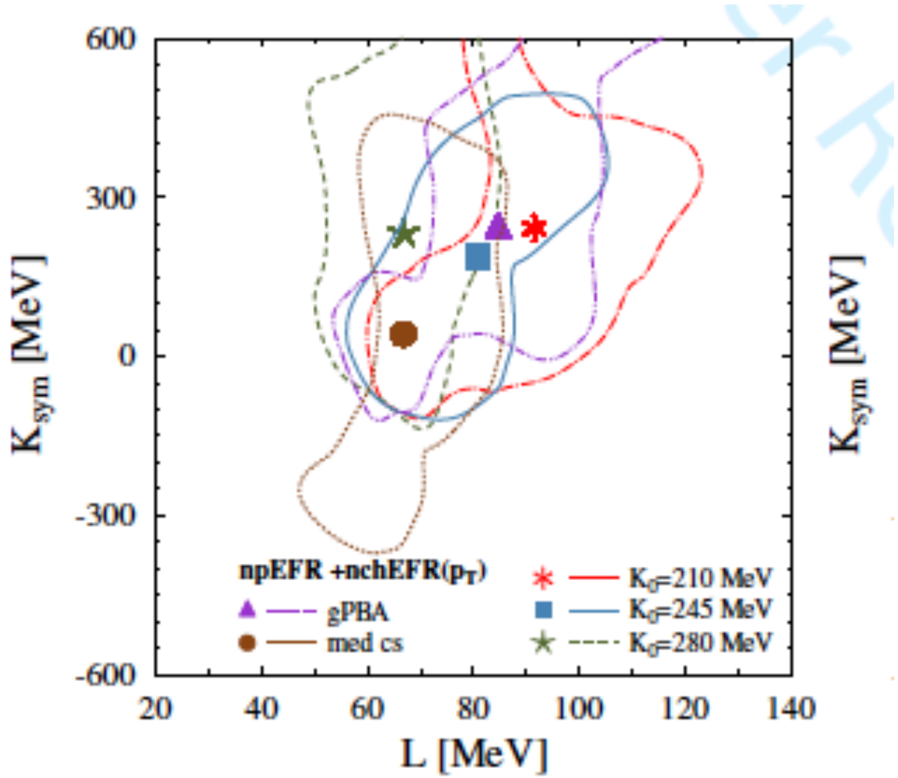


G. Colò, U. Garg, H. Sagawa, Eur. Phys. J. A 50, 26 (2014)

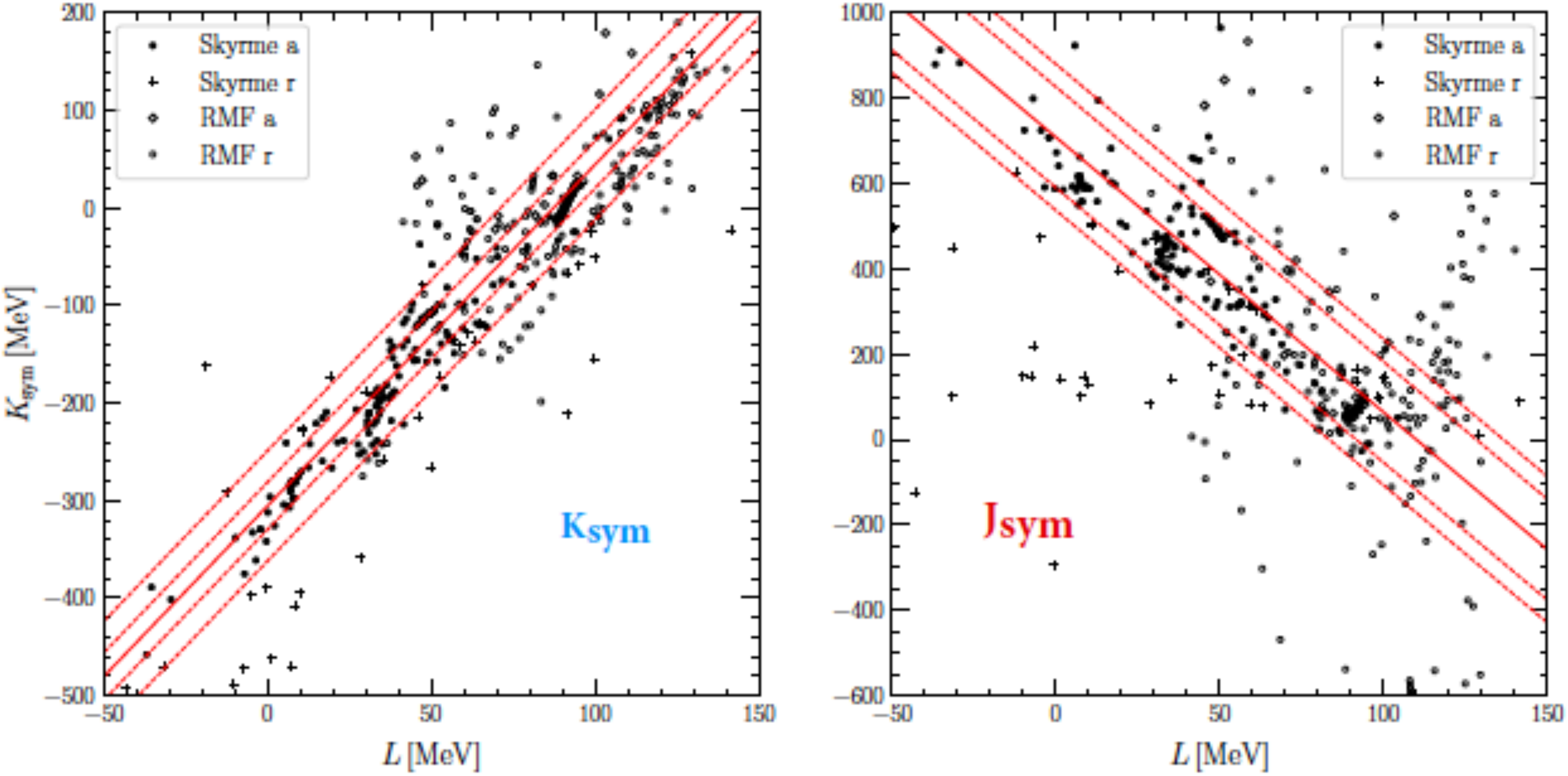
QMD analysis of GSI data on neutron-proton relative elliptical flow

Dan Cozma, Euro Phys. J. A 54: 40 (2018).

$$L = 85 \pm 22(\mathrm{exp}) \pm 20(\mathrm{th}) \pm 12(\mathrm{sys})\ \mathrm{MeV}$$
$$K_{sym} = 96 \pm 315(\mathrm{exp}) \pm 170(\mathrm{th}) \pm 166(\mathrm{sys})\ \mathrm{MeV}.$$



Systematics from over 520 Skyrme+RMF energy density functionals

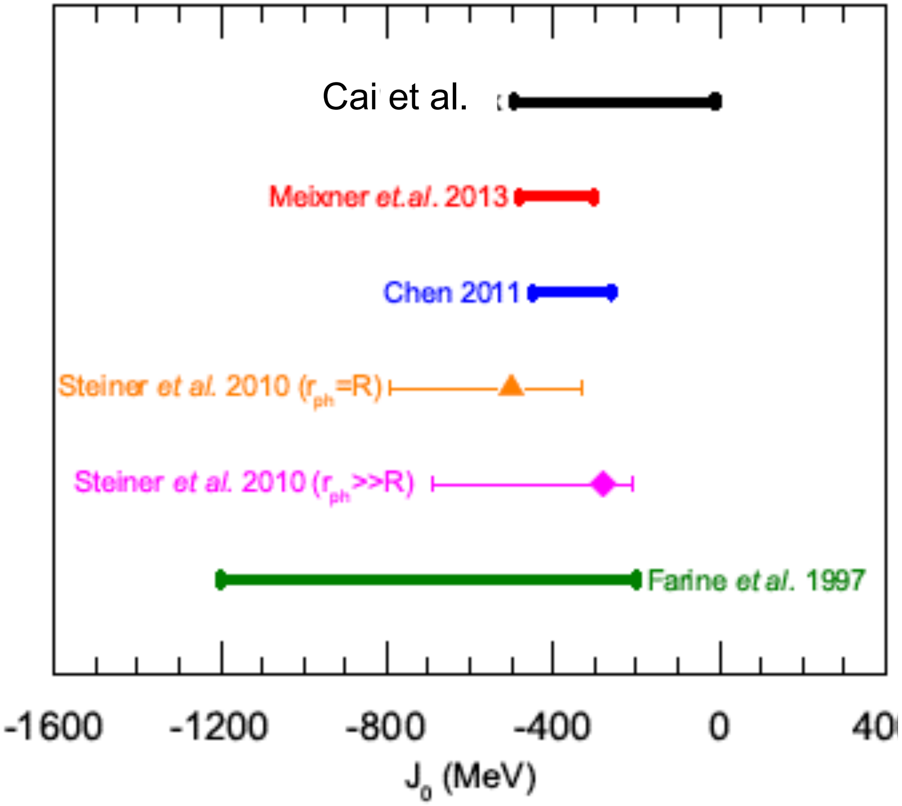


Ingo Tews, James M. Lattimer, Akira Ohnishi, Evgeni E. Kolomeitsev
Astrophysics J. 848, 105 (2017)

$$E_{\rm sym}(\rho) = E_{\rm sym}(\rho_0) + \frac{L}{3}(\frac{\rho}{\rho_0} - 1) + \frac{K_{\rm sym}}{18}(\frac{\rho}{\rho_0} - 1)^2 + \frac{J_{\rm sym}}{162}(\frac{\rho}{\rho_0} - 1)^3$$

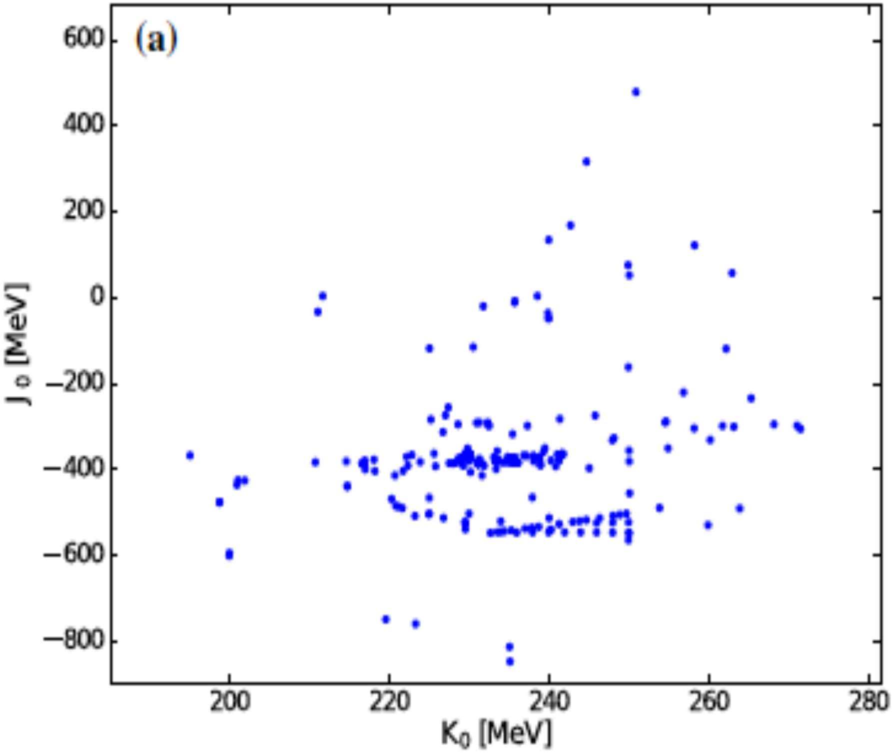
Skewness J_0 of symmetric matter

Indications from model analyses of data



B.J. Cai & L.W. Chen, Nucl. Sci. Tech., 28, 185 (2017)
A. W. Steiner, J.M. Lattimer & E. F. Brown, APJ, 722, 33 (2010).

173 Skyrme+101 RMF predictions



N.B. Zhang et al., Nucl. Sci. Tech., 28, 181 (2017)
P. Danielewicz, R. Lacey, & W.G. Lynch, Science, 298, 1592 (2002)

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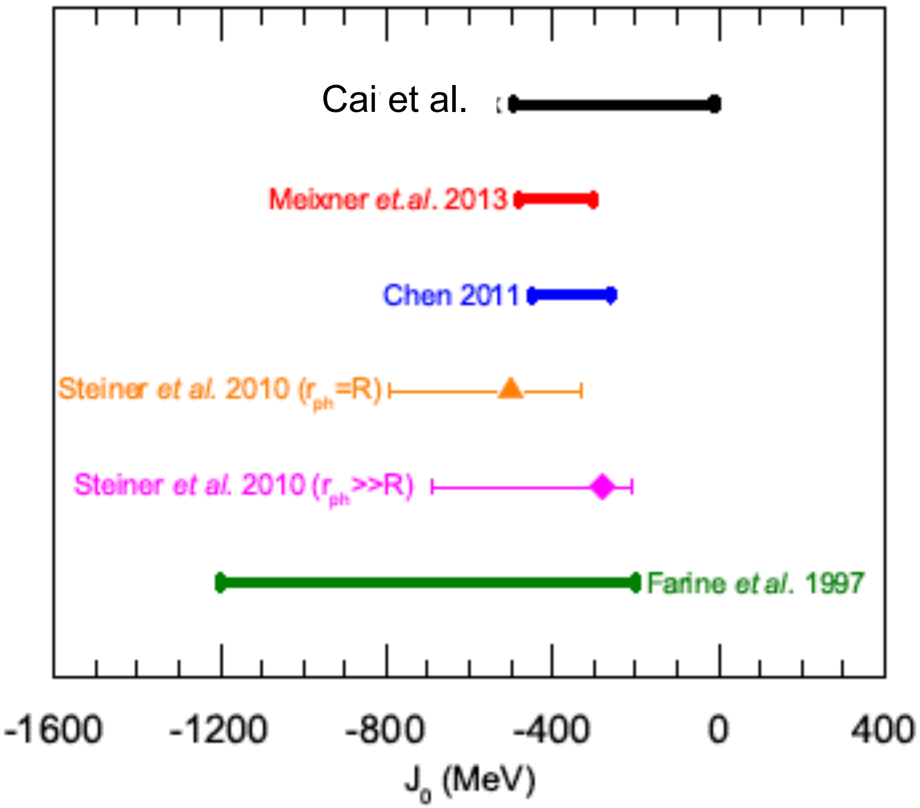

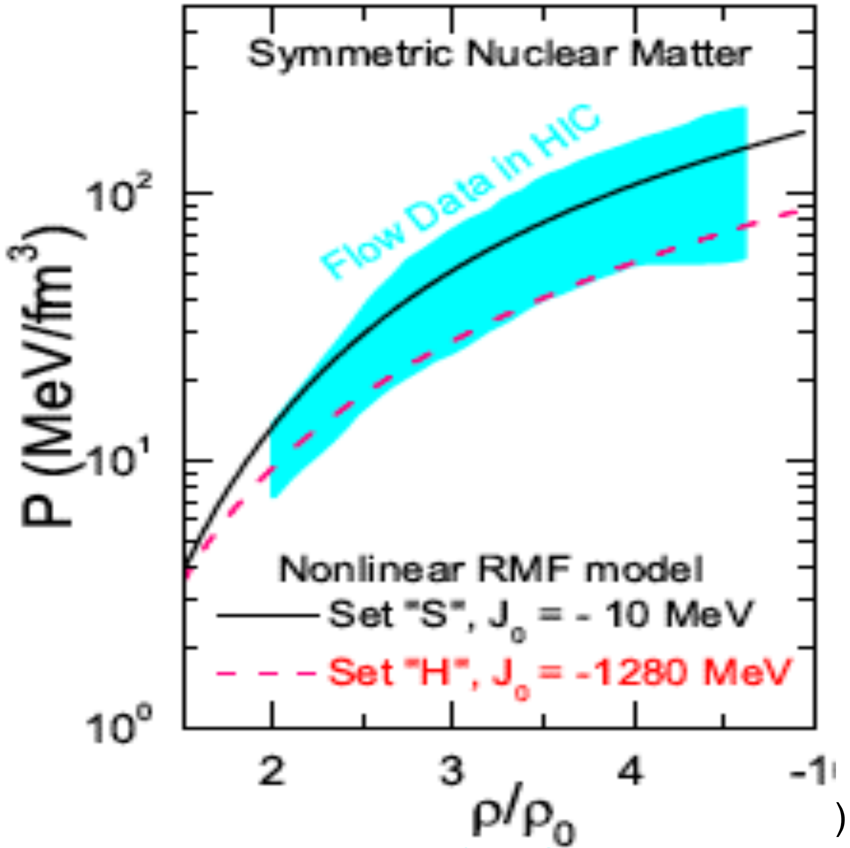

B.J. Cai & L.W. Chen, Nucl. Sci. Tech., 28, 185 (2017)
A. W. Steiner, J.M. Lattimer & E. F. Brown, APJ, 722, 33 (2010).

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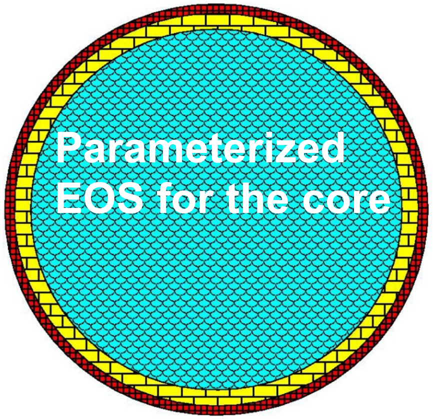
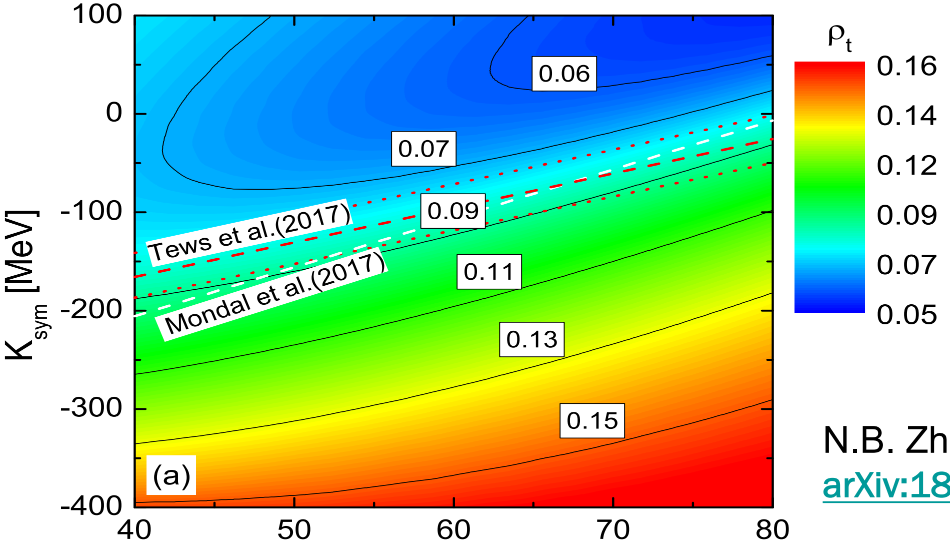
Effects of symmetry energy on the crust-core transition density

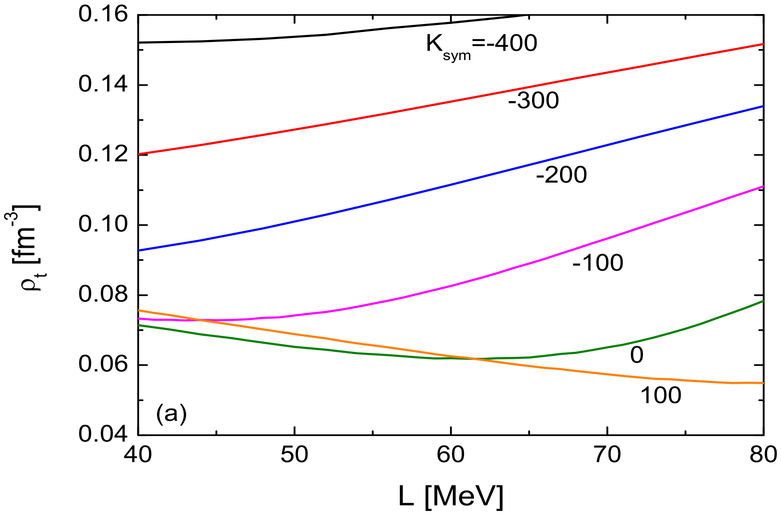


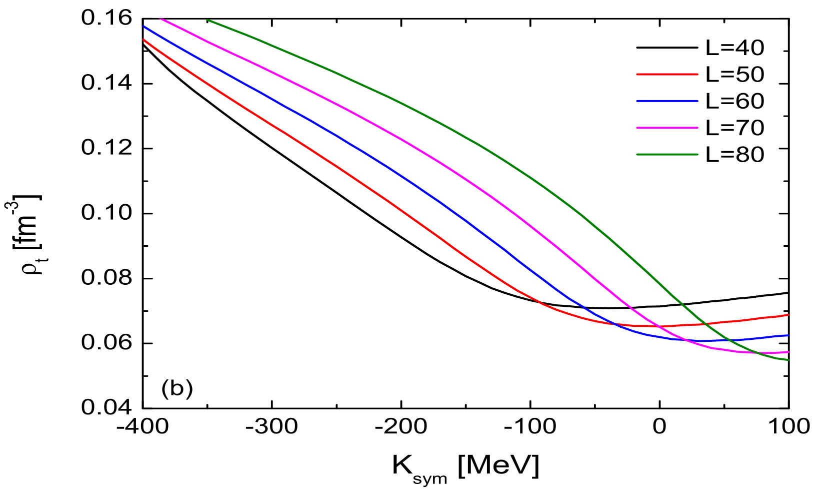
Parameterized EOS for the core

NV+BPS EOS
for the crust



N.B. Zhang, B.A. Li and J. Xu,
arXiv:1801.06855



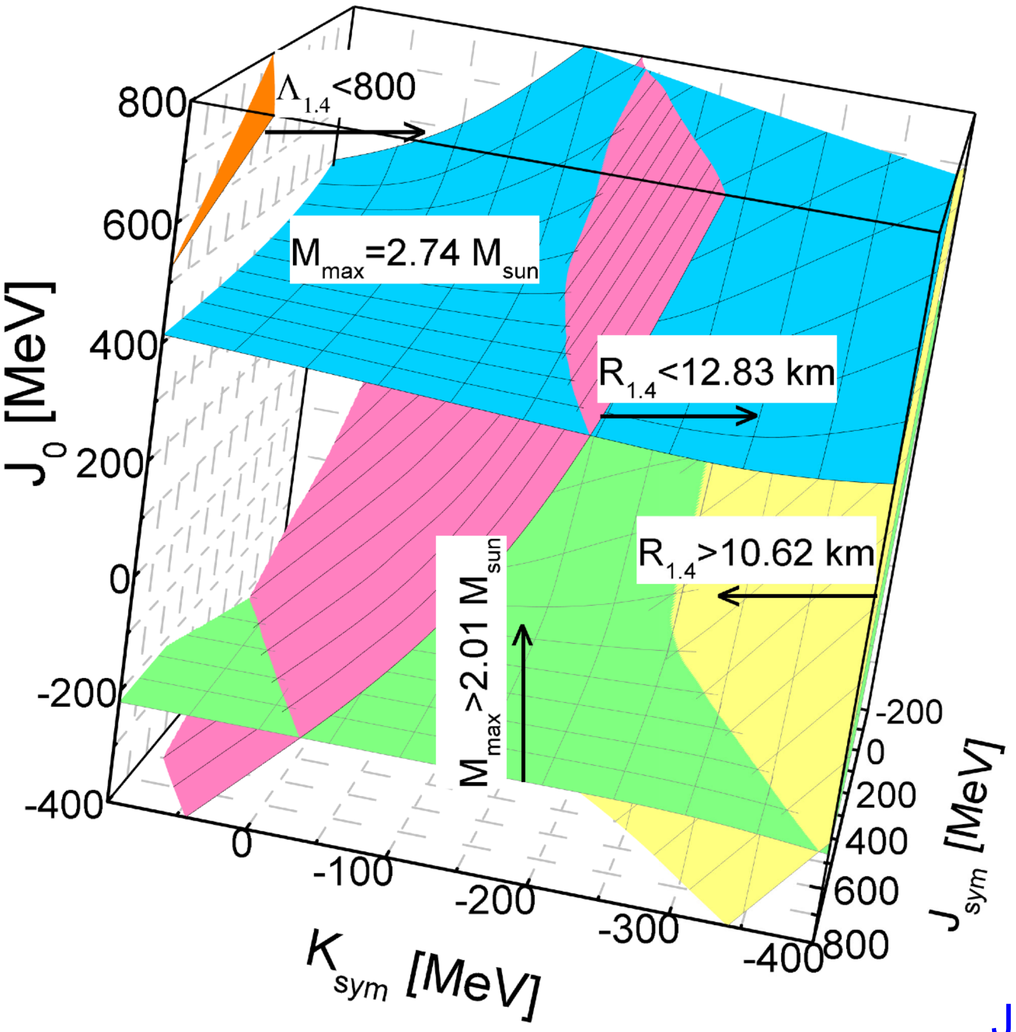


At the crust-core transition: Incompressibility in neutron stars at β equilibrium $= 0$

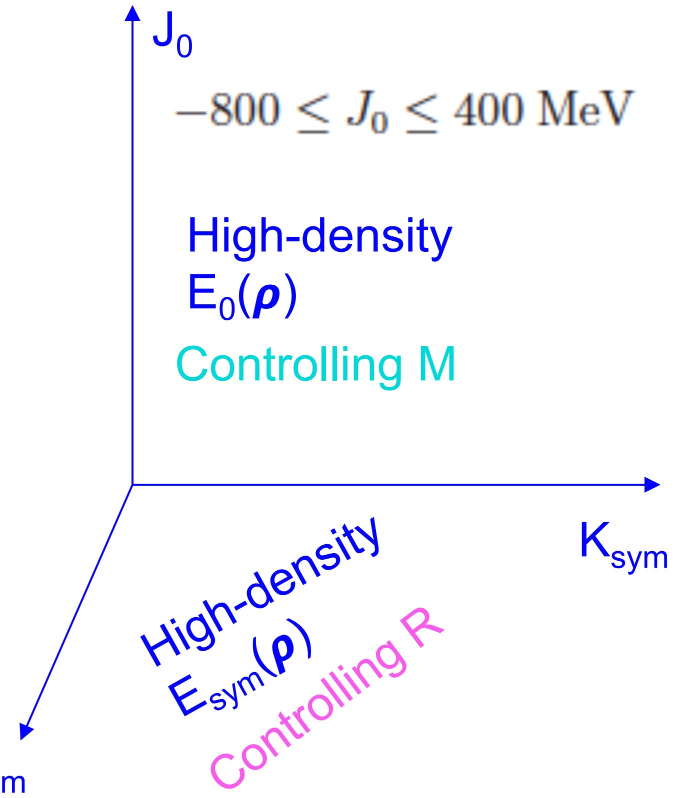
$$K_\mu = \rho^2 \frac{d^2 E_0}{d\rho^2} + 2\rho \frac{dE_0}{d\rho} + \delta^2 \left[\rho^2 \frac{d^2 E_{sym}}{d\rho^2} + 2\rho \frac{dE_{sym}}{d\rho} - 2E_{sym}^{-1} (\rho \frac{dE_{sym}}{d\rho})^2 \right]$$

Lattimer & Prakash, Phys. Rep., 442, 109 (2007)

Astrophysical constraints on the high-density EOS parameters in 3D



Low-density parameters are fixed at their most probable values



J_0

$$-800 \le J_0 \le 400 \text{ MeV}$$

High-density $E_0(\rho)$

Controlling M

K_{sym}

J_{sym}

High-density $E_{sym}(\rho)$

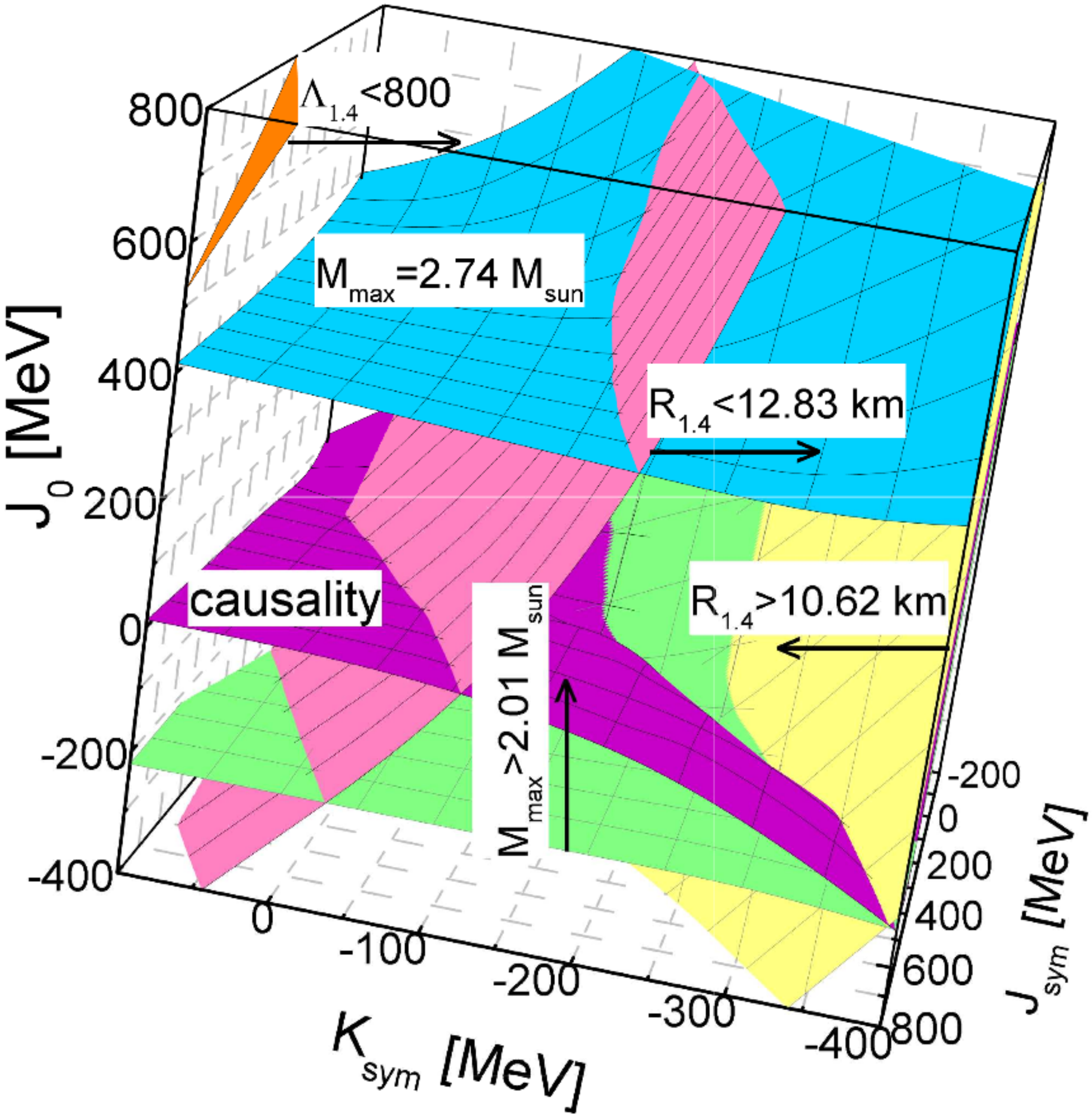
Controlling R

Degeneracy:

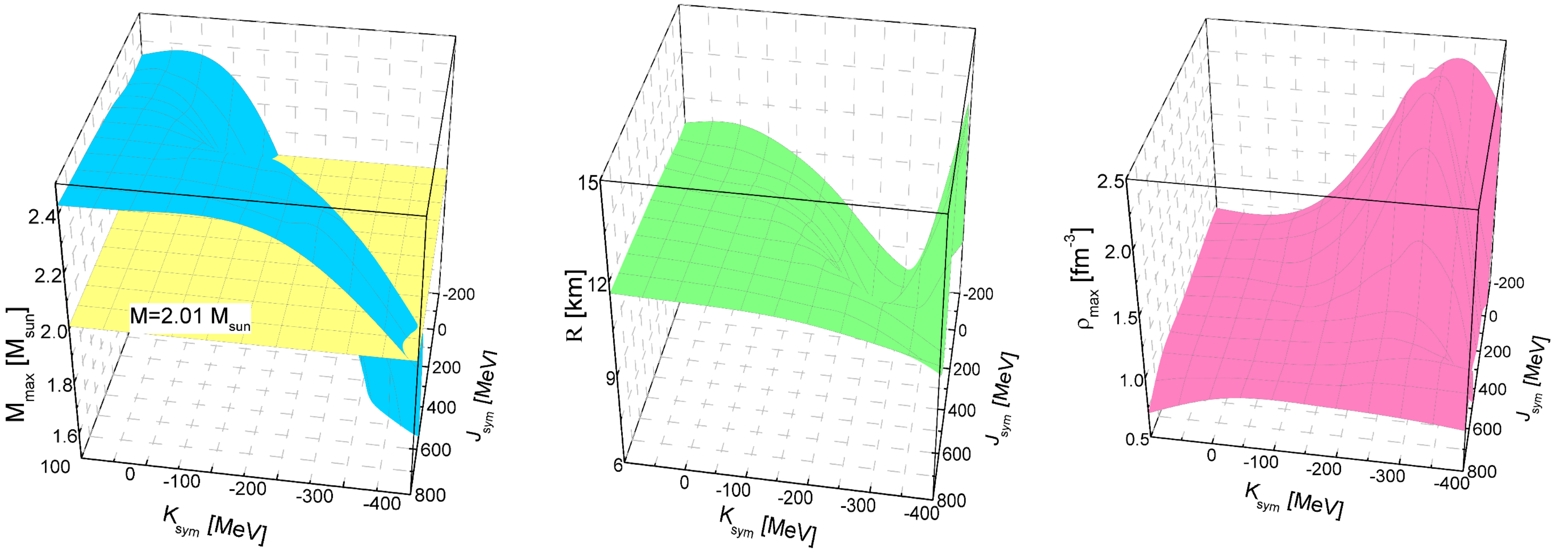
Intersections-> different EOS parameters giving identical M&R, same R different M or same M different R, **have to fix E_{sym} at HD to break it**

Causality, not the blue sky, is the upper limit!

It is impossible to form a stable hyper-massive NS with $M=2.74M_\odot$

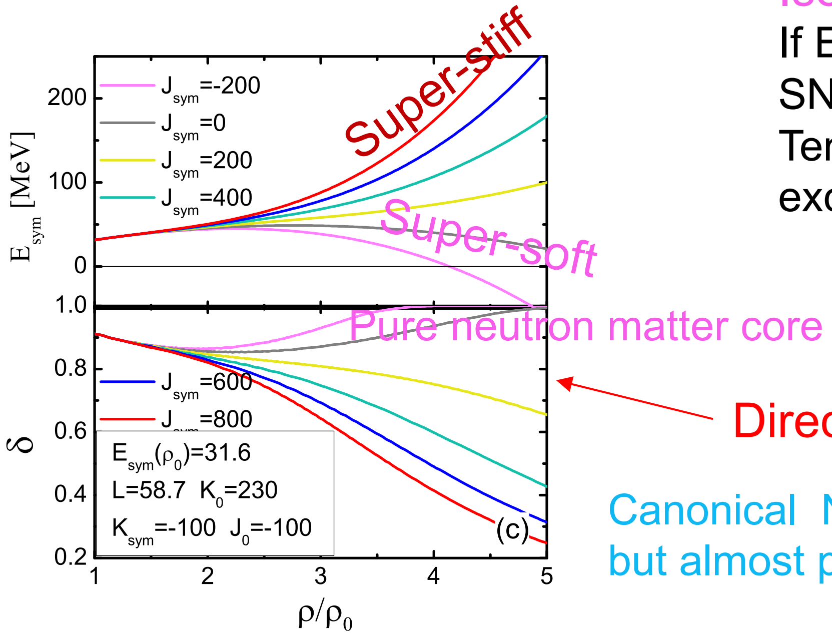


The maximum mass, radius and density on the causality surface



symmetry energy

Isospin asymmetry profile at beta equilibrium



Isospin separation instability:

If $E_{sym}<0$, replace **δ**=0 with 1+ (-1)

SNM=PNM+PPM to lower energy

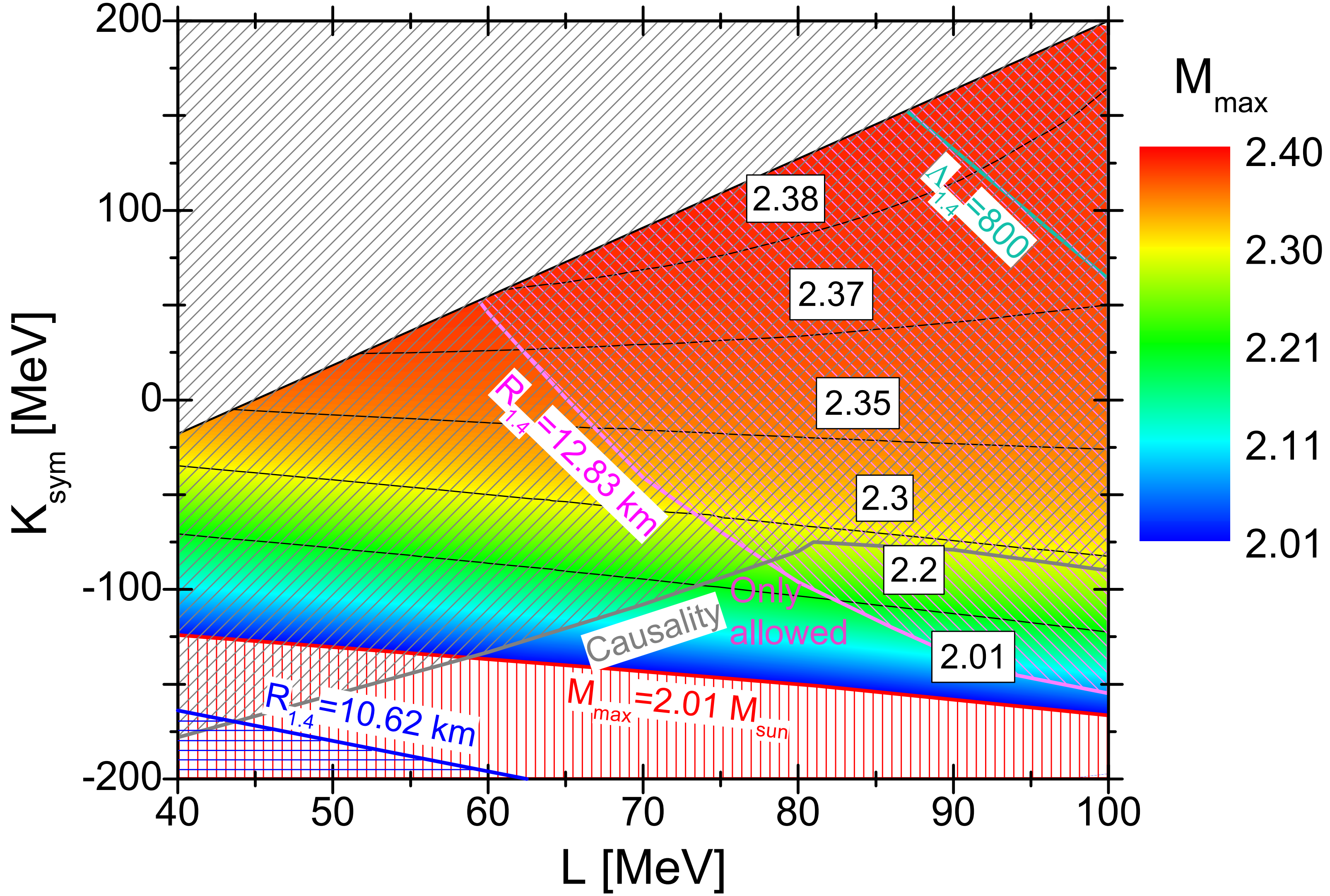
Tensor force in n-p due to ***ρ*** meson exchange can make this happen

$$E(\rho,\delta) \approx E_0(\rho) + E_{\mathrm{sym}}(\rho)\delta^2$$

Direct URCA limit

Canonical NSs have high core density, but almost pure neutrons → slow cooling

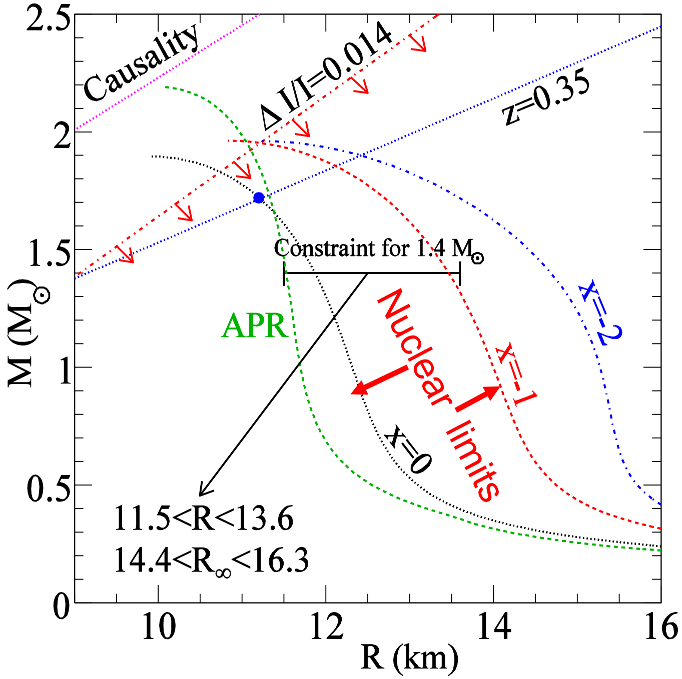
Setting $J_0=0$, $J_{sym}=0$, parameterizing the EOS quadratically in ρ and δ in 2D



N.B. Zhang, B.A. Li and J. Xu, arXiv:1801.06855

Constraining the radii of neutron stars with terrestrial experiments

Bao-An Li and Andrew W. Steiner, Phys. Lett. B642, 436 (2006)



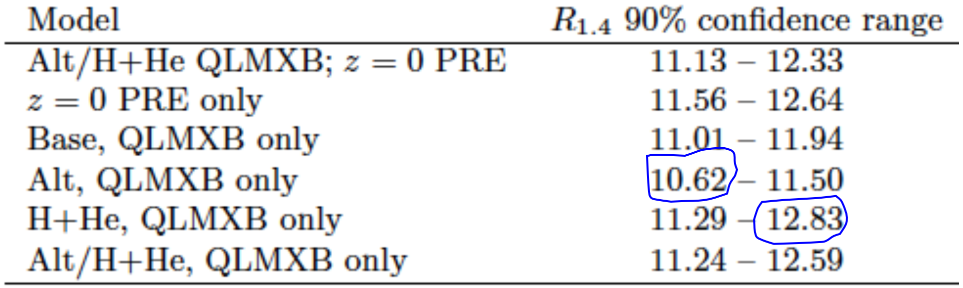
Nuclear limits

APR: K_0=269 MeV.

Radii of neutron stars inferred from observations

(a) thermal emissions from quiescent neutron star low-mass X-ray binaries (qLMXBs)

(b) photospheric radius expansion (PRE) bursts with H and/or He atmosphere models

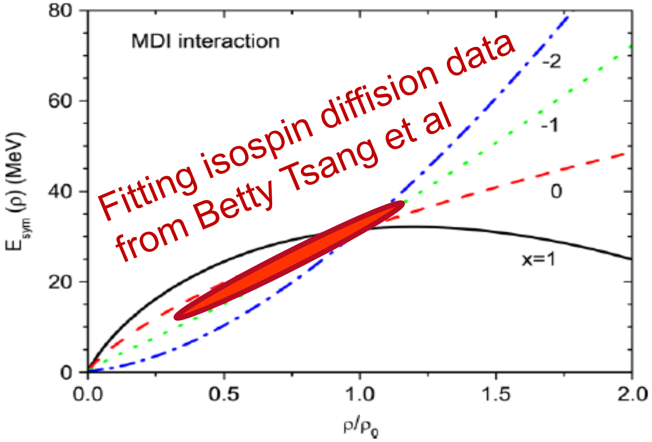


Model	$R_{1.4}$ 90% confidence range
Alt/H+He QLMXB; $z = 0$ PRE	11.13 – 12.33
$z = 0$ PRE only	11.56 – 12.64
Base, QLMXB only	11.01 – 11.94
Alt, QLMXB only	10.62 – 11.50
H+He, QLMXB only	11.29 – 12.83
Alt/H+He, QLMXB only	11.24 – 12.59

J.M. Lattimer and A.W. Steiner,
European Physics Journal A50, 40 (2014)

Review of techniques & controversies:

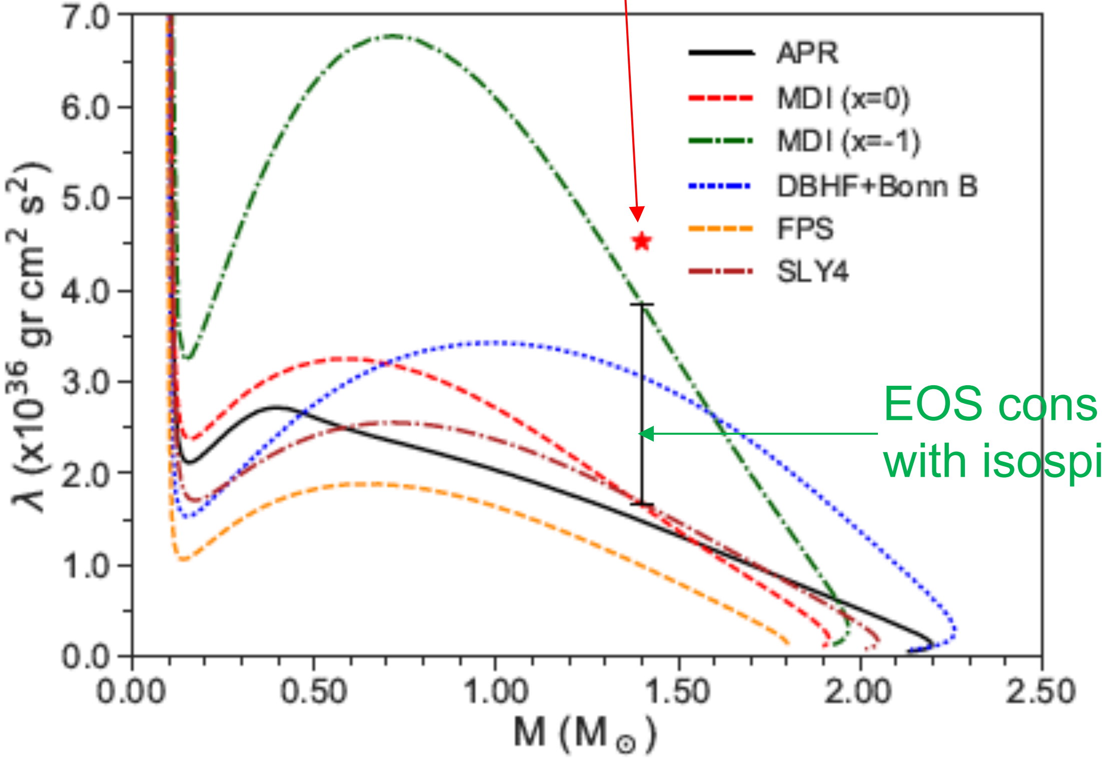
M.C. Miller & F.K. Lamb,
European Physical Journal A 52, 63 (2016).



Fitting isospin diffision data from Betty Tsang et al

L.W. Chen, C.M. Ko and B.A. Li,
Phys. Rev. Lett 94, 32701 (2005)

Imprints of nuclear E_{sym} on the tidal deformability of neutron stars

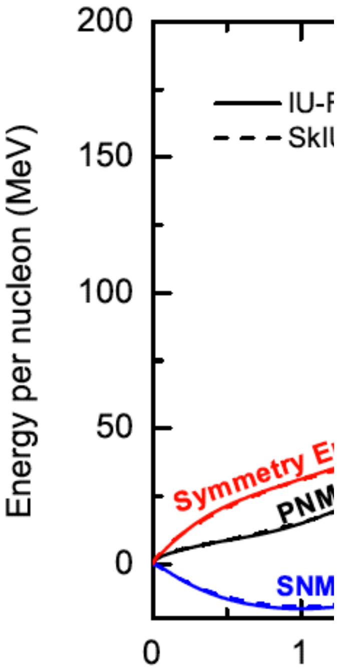


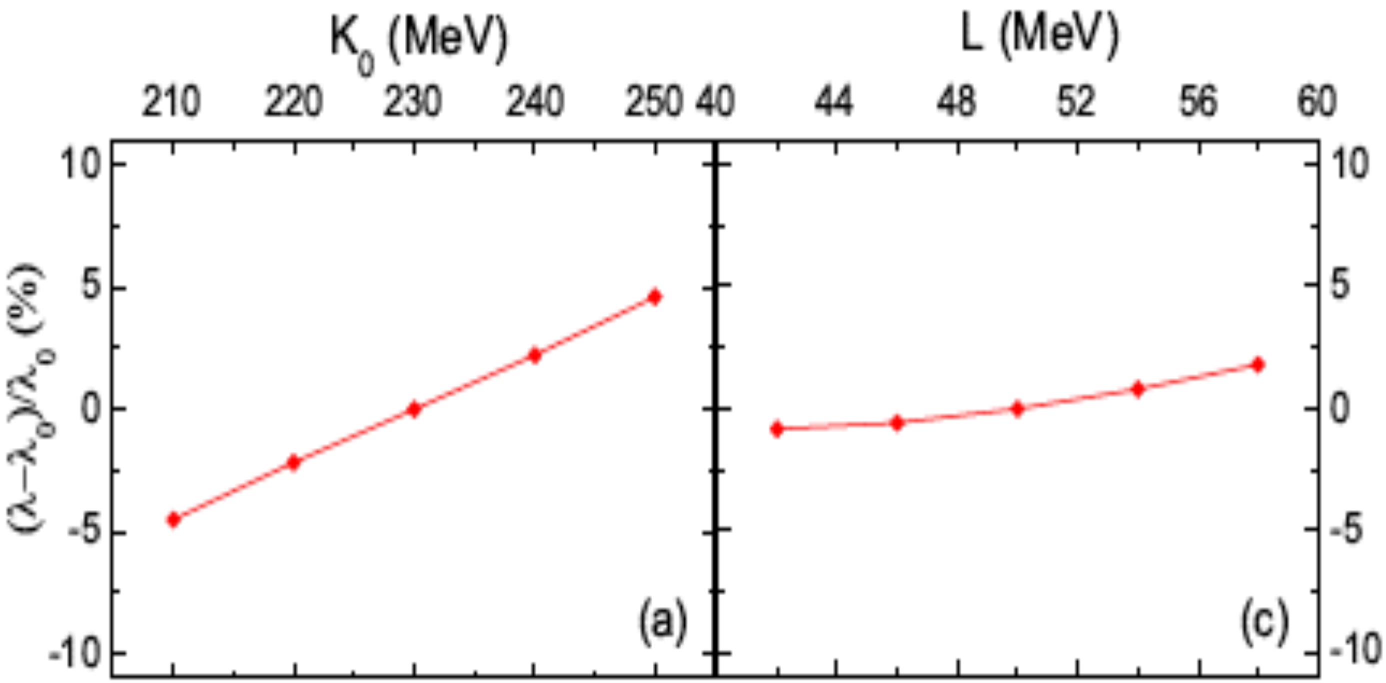
Upper limit from GW170817

EOS consistent
with isospin diffusion

Plamen G. Krastev, Bao-An Li **arXiv:1801.04620**

Signatures of S,L($n>n_0$) in GW signals: Tidal deformability and mergers





F. Fattoyev, J. Carvajal, W.G. Newton and B.A. Li, PRC87, 15806 (2013)

Λ of light NS is sensitive to L

Λ of canonical and more massive NS is sensitive to high-density E_{sym} but not L

- Detector sensitivities assuming optimally oriented, equal mass binary at D=100 Mpc

- *Damour, Nagar, PRD81, 084016 (2010)*
- *Damour, Nagar, Villain, PRD85, 123007 (2012)*
- *Hinderer et al, PRD 81, 123016 (2010)*

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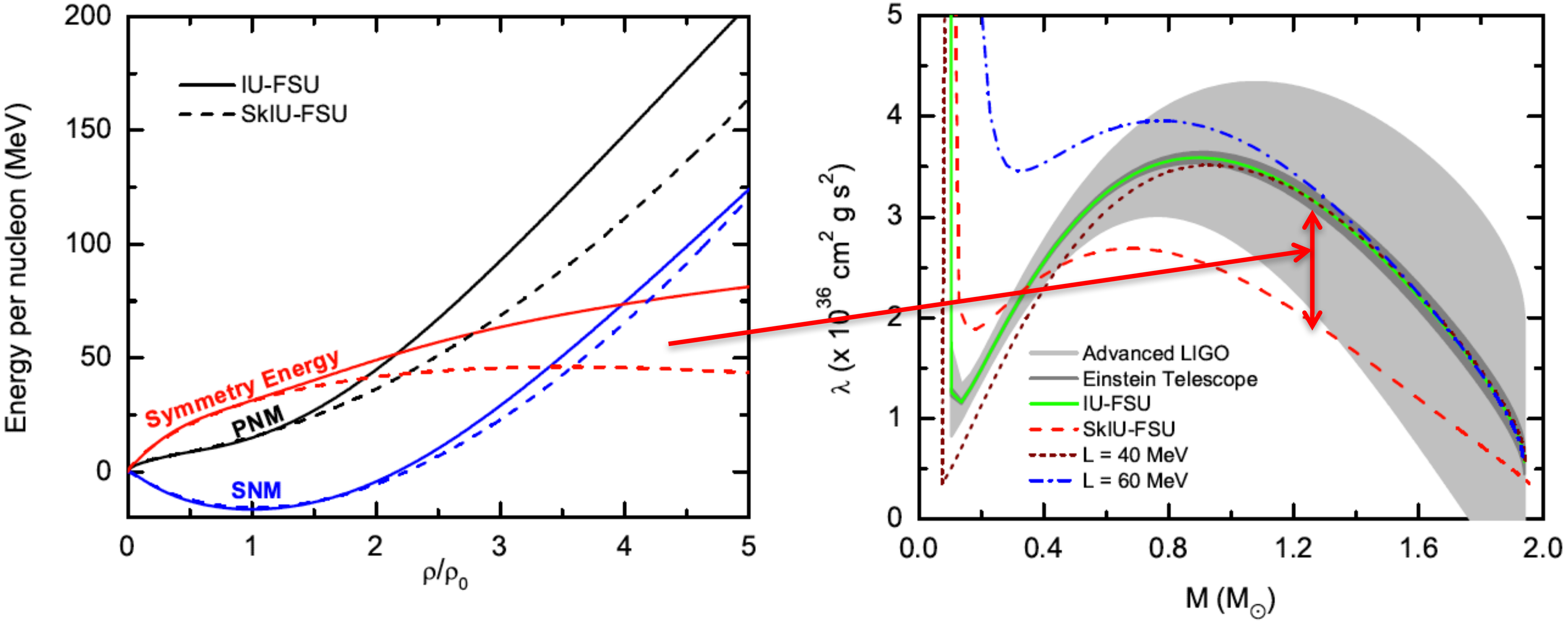

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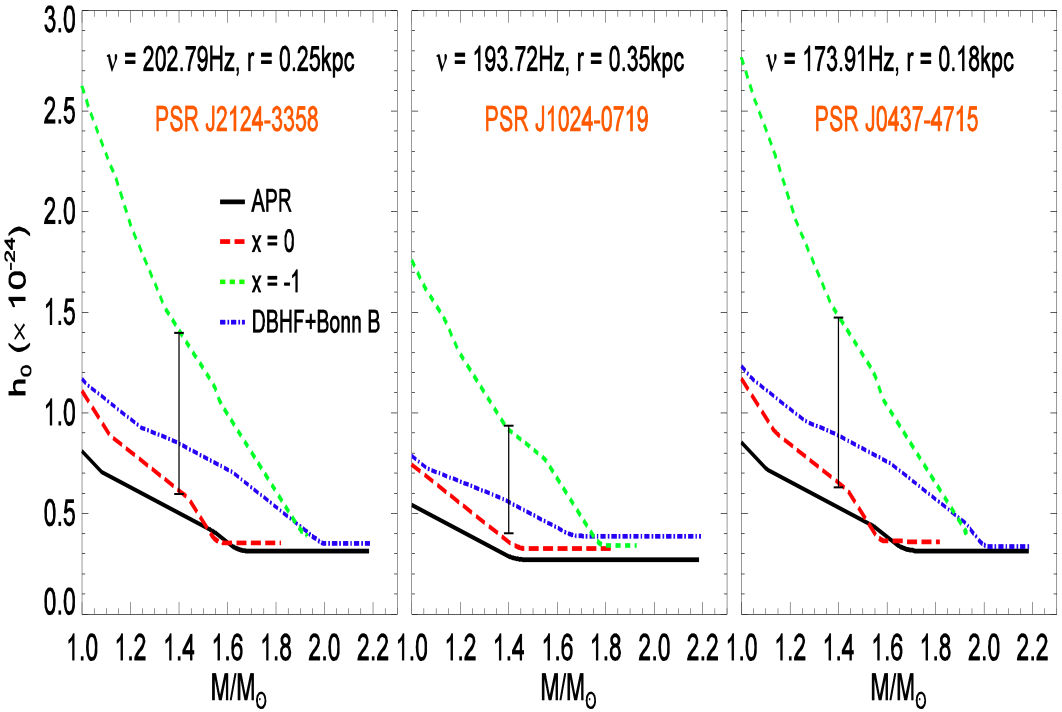
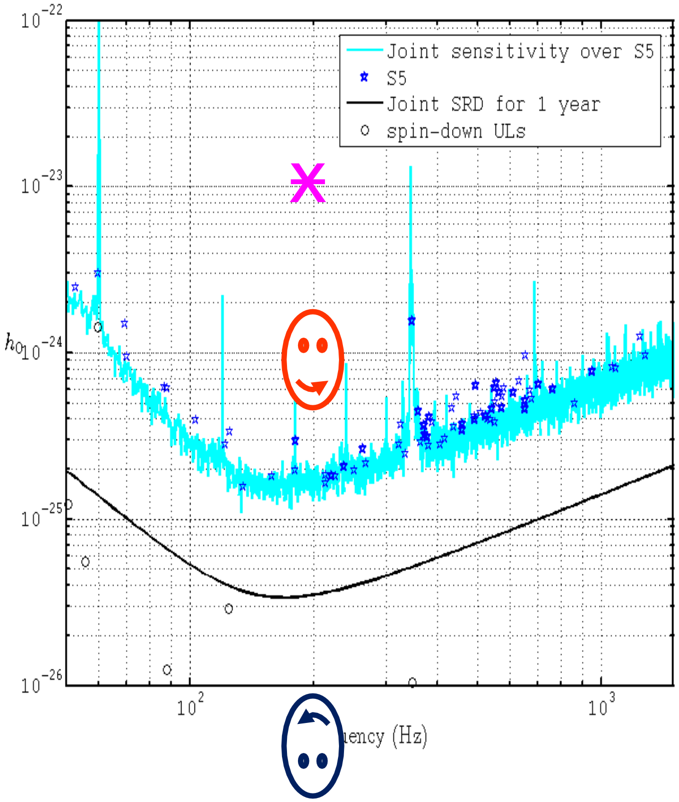
- *Hinderer et al, PRD 81, 123016 (2010)*

Nuclear constraints on the strength of gravitational waves

Plamen Krastev, Bao-An Li and Aaron Worley, Phys. Lett. B668, 1 (2008).



Compare with the latest upper limits from LIGO+GEO observations



σ is the breaking strain of the neutron star crust

$$\sigma = [10^{-5} - 10^{-2}]$$ or 0.1

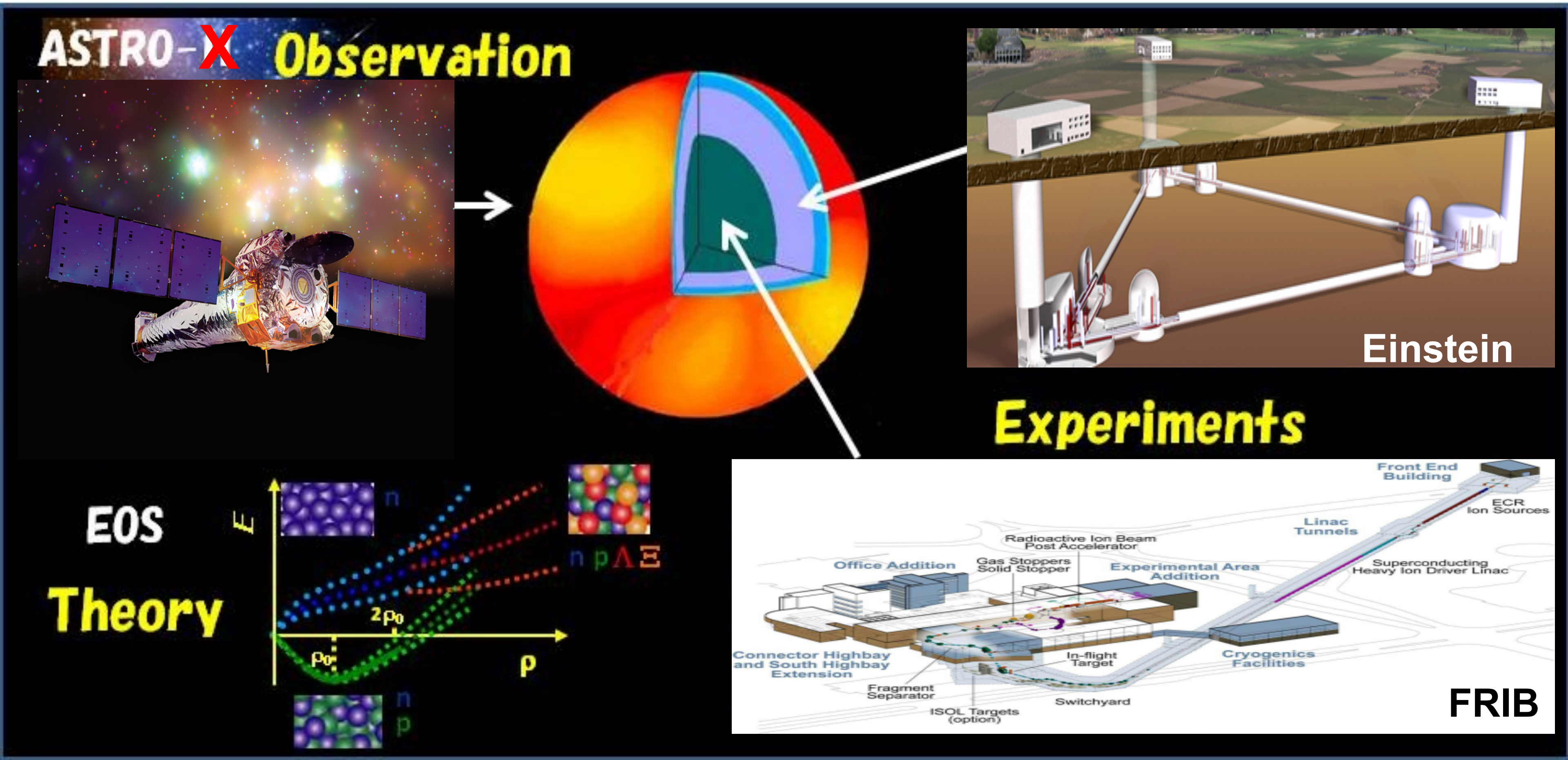
Depends on the symmetry energy and structure of NS

$$\Phi_{22,max} = 2.4 \times 10^{38} g\ cm^2 \left(\frac{\sigma}{10^{-2}}\right)\left(\frac{R}{10km}\right)^{6.26}\left(\frac{1.4M_\odot}{M}\right)^{1.2}$$

Summary

(1) Truly multi-messenger approach to probe the EOS of dense neutron-rich matter = astrophysical observations + terrestrial experiments + theories + …

(2) The upper limit $\Lambda(1.4M_\odot) < 800$ from GW170817 is consistent but less restrictive than the existing constraints on the EOS from the M_{max} and $R_{1.4}$



EOS of dense neutron-rich matter: a major scientific thrust of

(0) 2015 US and 2017 Europe Long Range Plan for Nuclear Physics
(1) High-energy rare isotope beam facilities around the world
(2) Neutron Star Interior Composition Explorer (NICER of NASA, lunched on June 3rd, to take science data on July 13th, 2017) and various x-ray satellite (Chandra, LOFT, XMM-Newton, etc)
(3) Various gravitational wave detectors

Among the promising observables of high-density symmetry energy:

- $\underline{\pi^-/\pi^+}$, neutron-proton differential flow in heavy-ion collisions
- Radii of neutron stars
- Neutrino flux of supernova explosions
- Strain amplitude and frequency of gravitational waves from spiraling neutron star binaries and/or oscillations/rotations of deformed pulsars

Topical Issue on Nuclear Symmetry Energy
edited by Bao-An Li, Àngels Ramos,
Giuseppe Verde and Isaac Vidaña

Euro Phys. Jour. A, Vol. 50, No. 2 (2014)

Can the symmetry energy become negative at high densities?

Yes, it happens when the tensor force due to ρ exchange in the T=0 channel dominates

At high densities, the energy of pure neutron matter can be lower than symmetric matter leading to negative symmetry energy

Pandharipande V R and Garde V K 1972 *Phys. Lett.* B **39** 608
Wiringa R B, Fiks V and Fabrocini A 1988 *Phys. Rev.* C **38** 1010

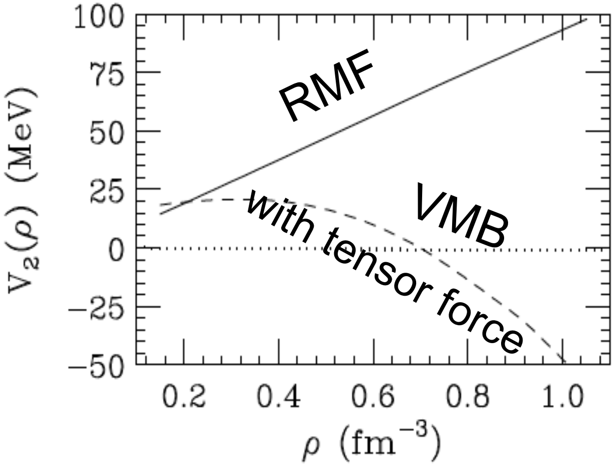
Kutschera M 1994 *Phys. Lett.* B **340** 1

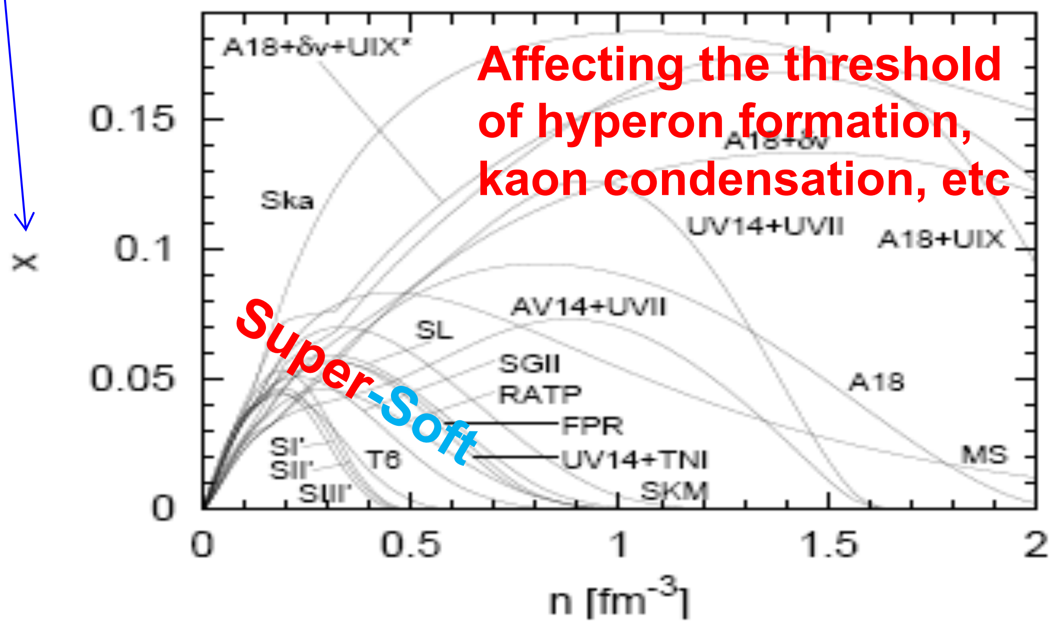
Example: proton fractions with interactions/models leading to negative symmetry energy

M. Kutschera et al., Acta Physica Polonica B37 (2006)

$$x = 0.048[E_{sym}(\rho)/E_{sym}(\rho_0)]^3(\rho/\rho_0)(1-2x)^3$$

Potential part of the symmetry energy





Affecting the threshold of hyperon formation, kaon condensation, etc

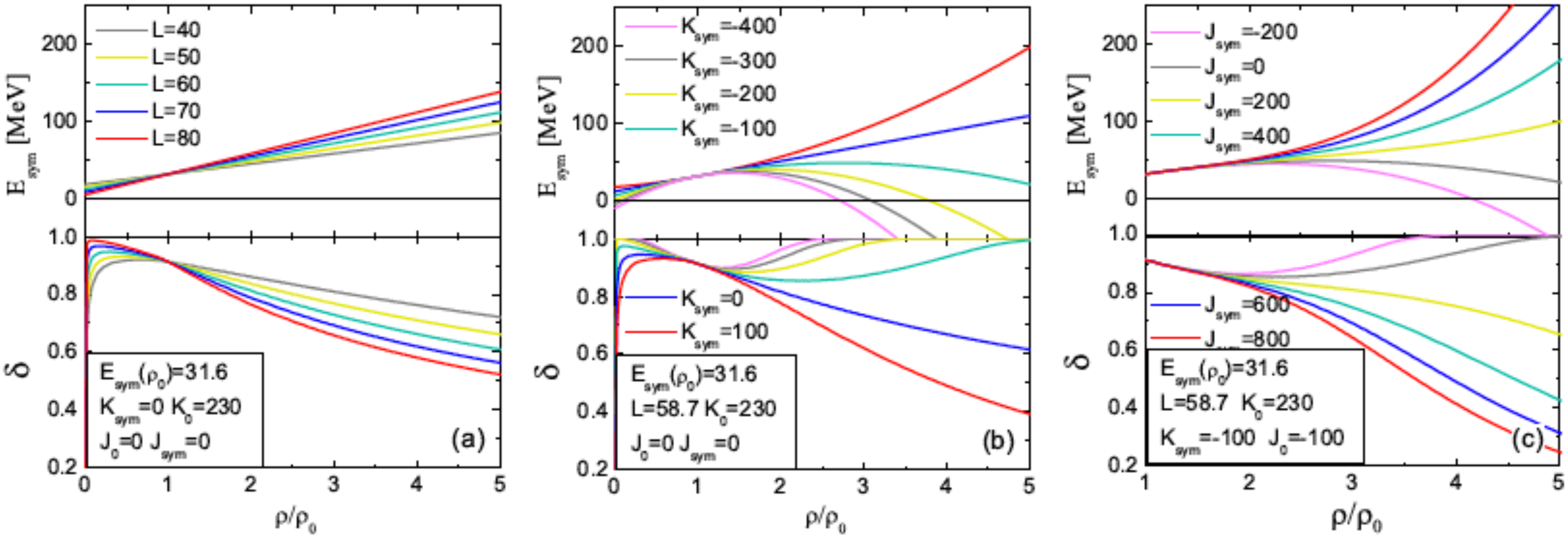
Super-Soft

Tensor force and/or 3-body force can make E_{sym} negative at high densities

3-body force effects
in Gogny or Skyrme HF

$$V_d = t_0(1 + x_0P_\sigma)\rho^\alpha\delta(r),$$

$$E^{TBF}_{sym} = -(1+2x_0)\frac{t_0}{8}\rho^{\alpha+1}$$



E_{sym} [MeV]
δ
ρ/ρ_0
L=40
L=50
L=60
L=70
L=80
$E_{sym}(\rho_0)$=31.6
K_{sym}=0 K_0=230
J_0=0 J_{sym}=0
(a)
K_{sym}=-400
K_{sym}=-300
K_{sym}=-200
K_{sym}=-100
K_{sym}=0
K_{sym}=100
$E_{sym}(\rho_0)$=31.6
L=58.7 K_0=230
J_0=0 J_{sym}=0
(b)
J_{sym}=-200
J_{sym}=0
J_{sym}=200
J_{sym}=400
J_{sym}=600
J_{sym}=800
$E_{sym}(\rho_0)$=31.6
L=58.7 K_0=230
K_{sym}=-100 J_0=-100
(c)
0
100
200
0.2
0.4
0.6
0.8
1.0
0
1
2
3
4
5

The proton fraction x at ß-equilibrium in proto-neutron stars is determined by

$$x = 0.048[E_{sym}(\rho)/E_{sym}(\rho_0)]^3(\rho/\rho_0)(1-2x)^3$$

The critical proton fraction for direct URCA process to happen is X_p=0.14 for npeμ matter obtained from energy-momentum conservation on the proton Fermi surface

Slow cooling: modified URCA:

$$n+(n,p)\rightarrow p+(n,p)+e^-+\overline{\nu}_e$$

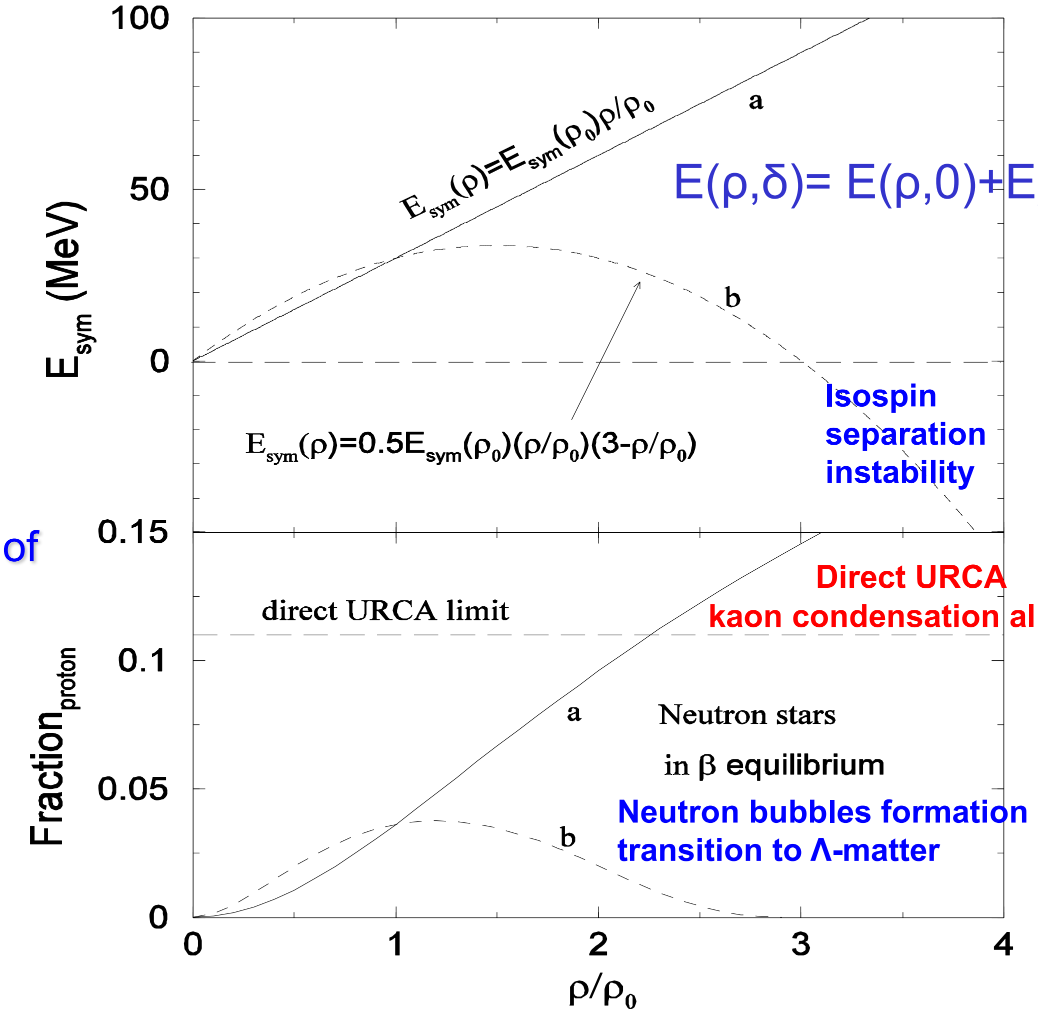
$$p+(n,p)\rightarrow n+(n,p)+e^++\nu_e$$

Consequence: long surface thermal emission up to a few million years

Faster cooling by 4 to 5 orders of magnitude: direct URCA

$$n \longrightarrow p+e^-+\overline{\nu}_e$$

$$p \longrightarrow n+e^++\nu_e$$



$E(\rho,\delta)= E(\rho,0)+E_{sym}(\rho)\delta^2$

Isospin separation instability

Direct URCA
kaon condensation allowed

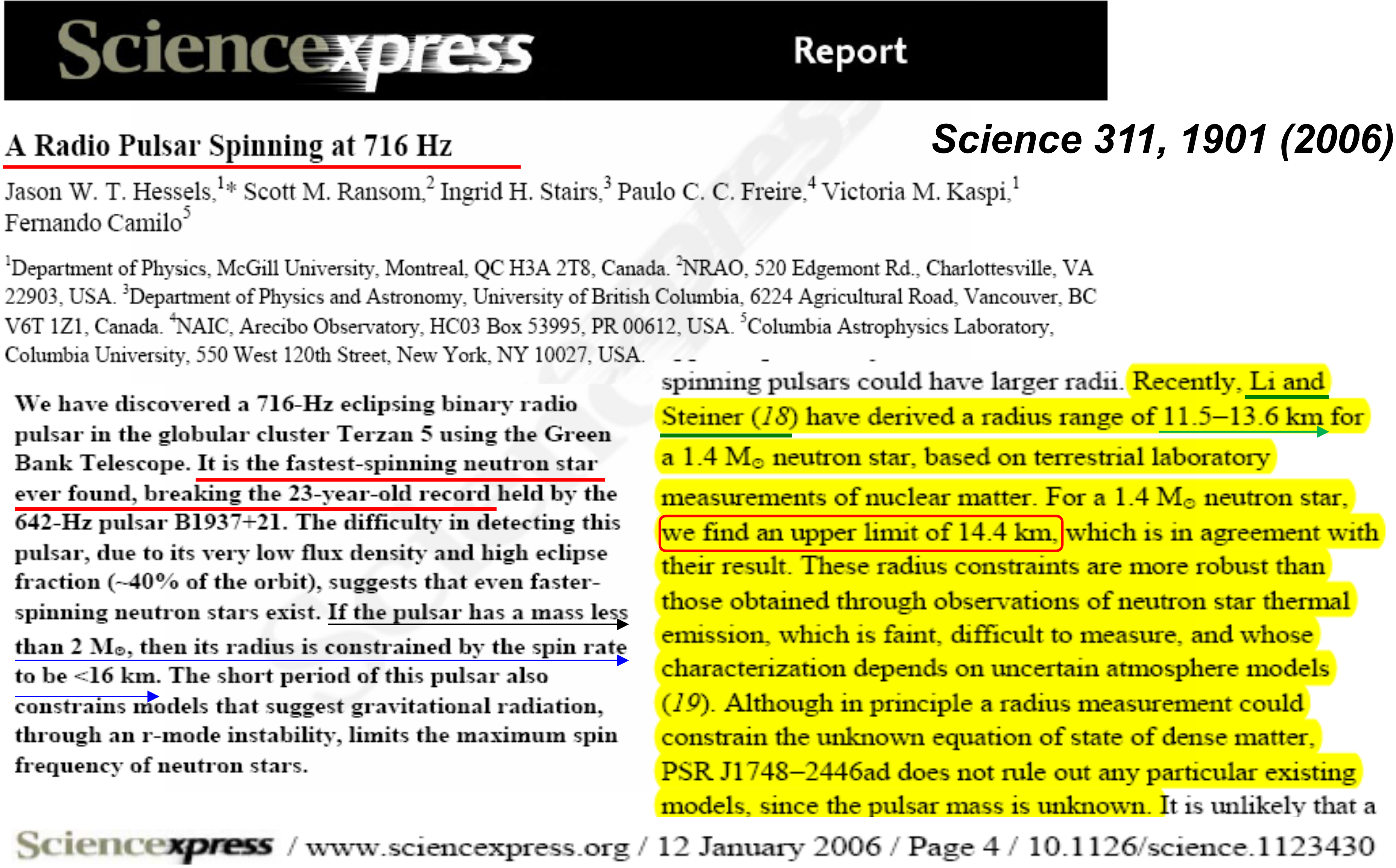
Neutron bubbles formation
transition to Λ-matter

Bao-An Li, Phys. Rev. Lett. 88 (2002) 192701

National Radio Astronomy Observatory

News Release on Jan. 12, 2006: Astronomers discover the fastest-spinning neutron-star

Science 311, 1901 (2006).



Sciencexpress Report

A Radio Pulsar Spinning at 716 Hz

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We have discovered a 716-Hz eclipsing binary radio pulsar in the globular cluster Terzan 5 using the Green Bank Telescope. It is the fastest-spinning neutron star ever found, breaking the 23-year-old record held by the 642-Hz pulsar B1937+21. The difficulty in detecting this pulsar, due to its very low flux density and high eclipse fraction (~40% of the orbit), suggests that even faster-spinning neutron stars exist. If the pulsar has a mass less than 2 $M_\odot$, then its radius is constrained by the spin rate to be <16 km. The short period of this pulsar also constrains models that suggest gravitational radiation, through an r-mode instability, limits the maximum spin frequency of neutron stars.

spinning pulsars could have larger radii. Recently, Li and Steiner (*18*) have derived a radius range of 11.5–13.6 km for a 1.4 $M_\odot$ neutron star, based on terrestrial laboratory measurements of nuclear matter. For a 1.4 $M_\odot$ neutron star, we find an upper limit of 14.4 km, which is in agreement with their result. These radius constraints are more robust than those obtained through observations of neutron star thermal emission, which is faint, difficult to measure, and whose characterization depends on uncertain atmosphere models (*19*). Although in principle a radius measurement could constrain the unknown equation of state of dense matter, PSR J1748–2446ad does not rule out any particular existing models, since the pulsar mass is unknown. It is unlikely that a

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